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JUMBO SPACE ENVIRONMENT SIMULATION AND SPACECRAFT CHARGING CHAMBER CHARACTERIZATION

Russell Cooper and Ryan Hoffman

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Technical Report

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14. ABSTRACT
The Spacecraft Charging and Instrument Calibration Laboratory (SCICL) is in the process of being updated at Kirtland AFB, Albuquerque, NM. SCICL will be a comprehensive one-stop shop for testing R&D spacecraft solar array coupons, novel materials, dielectric charging, and modeling of spacecraft effects from said materials. The Jumbo space environment chamber has been modified with new high energy electron, photon and ion sources to simulate the space environment. The system includes the ability to mount a variety of probes on an up to four axes motion system to generate accurate characterization of the environmental sources. The first experiments planned for the Jumbo chamber are measuring the charge transport characteristics of insulating materials. This work requires measuring the sample surface potential with non-contact electrostatic probes during exposure to an electron beam. This technical report focuses on the capabilities upgrade to the Jumbo chamber as well as characterization of the various sources and probes used to create and measure the simulated space environment.

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Table of Contents

List of Figures

1. SUMMARY

The Spacecraft Charging and Instrument Calibration Laboratory (SCICL) is in the process of being updated at Kirtland AFB, Albuquerque, NM. SCICL will be a comprehensive one-stop shop for testing R&D spacecraft solar array coupons, novel materials, dielectric charging, and modeling of spacecraft effects from said materials. The Jumbo space environment chamber has been modified with new high energy electron, photon and ion sources to simulate the space environment. The system includes the ability to mount a variety of probes on an up to four axes motion system to generate accurate characterization of the environmental sources. The first experiments planned for the Jumbo chamber are measuring the charge transport characteristics of insulating materials. This work requires measuring the sample surface potential with non-contact electrostatic probes during exposure to an electron beam. This technical report focuses on the capabilities upgrade to the Jumbo chamber as well as characterization of the various sources and probes used to create and measure the simulated space environment.

2. INTRODUCTION

As a spacecraft interacts with the ambient plasma environment, it will adopt a voltage potential relative to the surrounding plasma. Its surfaces may also develop potentials relative to adjacent spacecraft components. If the voltage differential is sufficient, dielectric breakdown or plasma arcing will occur, resulting in damage ranging from minor material degradation to total mission failure.[1] These potentials are the result of the complex interactions of ions, electrons and photons from the environment and the materials of which the spacecraft is constructed.[1, 2] Although experimental studies of basic charging characteristics for common space materials have been undertaken for many years a clear understanding of what drives charge transport is not yet fully developed.[2-4] Additionally, although it is well established that materials age when exposed to the harsh space environment, little is known about the nature and extent of this aging. For example it has been reported that Kapton undergoes orders of magnitude change in resistivity in orbit although the exact extent of resistivity change has not been measured.[5] The Jumbo environmental simulation chamber has recently been adapted to measure the charge transport characteristics of polymer materials commonly used in spacecraft construction and how aging in simulated space environments alters these charge transport characteristics. To accomplish this task the chamber has been fitted with a new array of electron, photon and ion sources as well as a variety of diagnostic probes. Since the thrust of this study is to determine the storage and transport of charge in a dielectric material in space, the chamber has been tailored to

Figure 1: Spacecraft Charging and Instrument Calibration Laboratory in the Space Vehicles Directorate of AFRL at Kirtland AFB

generate environments containing highly energetic particles and measure surface potentials of space materials. The document outlines the capabilities of this experimental apparatus and characterizes its components.

3. JUMBO CHAMBER AND COMPONENTS

The Jumbo vacuum chamber is a 1.8m x 1.8m cylindrical chamber and resides within the Spacecraft Charging and Instrument Calibration Laboratory in the Space Vehicles Directorate of AFRL at Kirtland AFB (see Fig. 1). It has 20 ISO and Conflat (CF) ports ranging from 2.75” to 22”and a bevy of mechanical, gas and electrical feedthroughs. Jumbo is a completely dry-pumped chamber allowing minimal surface contamination of test materials. The chamber is primarily pumped with a two stage Sumitomo Marathon CP-20 cryo-pump operating at 13 K. The cryo-pump has a 20” aperture and a pumping speed of 582,000 L/min. It can take the chamber from rough vacuum (10^{-3} torr) to high vacuum (10^{-6} torr) in fifteen minutes. The cryo-pump is backed with an Alcatel ACG 600 which consists of a dry multi-stage roots pump and a roots blower, with a peak pumping speed of 8000L/min. The ACG 600 can rough pump the chamber from atmosphere to rough vacuum(10^{-3} torr) in fifteen minutes. There is an additional oil-free18” Mitsubishi FT3301W turbo-molecular pump, 360,000L/min that is backed with a 600L/min Varian tri-scroll dry pump. The Turbo pump, operating on its own, can bring the chamber to high vacuum in several hours, but is primarily used when gas is flowing into the chamber to avoid saturation of the cryo-pump.

Figure 2: Jumbo Environmental Simulation Chamber

Jumbo contains a thermal stage that can be cooled to liquid nitrogen (LN_2) temperatures and heated to 80^{o}C and is used as a sample mounting plate. For typical operations the stage is held perpendicular to the incident beams; however it can be swiveled to provide grazing incident angles. While not currently in operation, the stage can be used in conjunction with a LN_2 cryo-shroud to provide a 360^{o} simulated “cold view-to-space”.

Jumbo is also equipped with a four automated motion stages used for a variety of measurements. A three axis translational stage provides a moveable platform for various sensors and sample holders in Jumbo. These stages are automated with Phytron rad-hard stepper motors capable of controlling the location of any attached probes or samples with sub-millimeter resolution. Three of the stages are linear; two with a 24” range of travel and the third with 18”. The fourth stage is rotational with 0.4^{o} resolution and is used with a sample mounting wheel to rotate materials within the beam to normalize exposure. This system allows the sample carousel and probes to be moved closer to the location of the electron, ion and VUV sources. This allows some degree of control over the beam size and flux of each of the sources by taking advantage of geometric

factors, and will be discussed in greater detail later in the section covering the Jumbo's source capabilities.

The rotatable sample carousel is capable of holding eight different sample test coupons. However, one position is typically left empty to provide a control. Mounting multiple samples allows an increased testing rate and increases the consistency of the measurements made on each sample. The rotation of the wheel plays three important roles. First, all samples are exposed to the same portions of the electron, ion, or VUV beams ensuring each sample has been exposed to the same environment. Second, rotating the materials through the beam insures uniform exposure by averaging out spatially varying beam profiles. Third, instead of bringing a surface voltage probe in periodically to measure the samples, we are constantly measuring the surface potential of the samples as they are exposed. The carousel platform has the capacity to hold any of the diagnostic probes such as Faraday cups or Langmuir probes needed to monitor conditions during the test. The platform can be mounted anyplace in the chamber, however it is most often mounted to the 3-axis stage for greater flexibility.

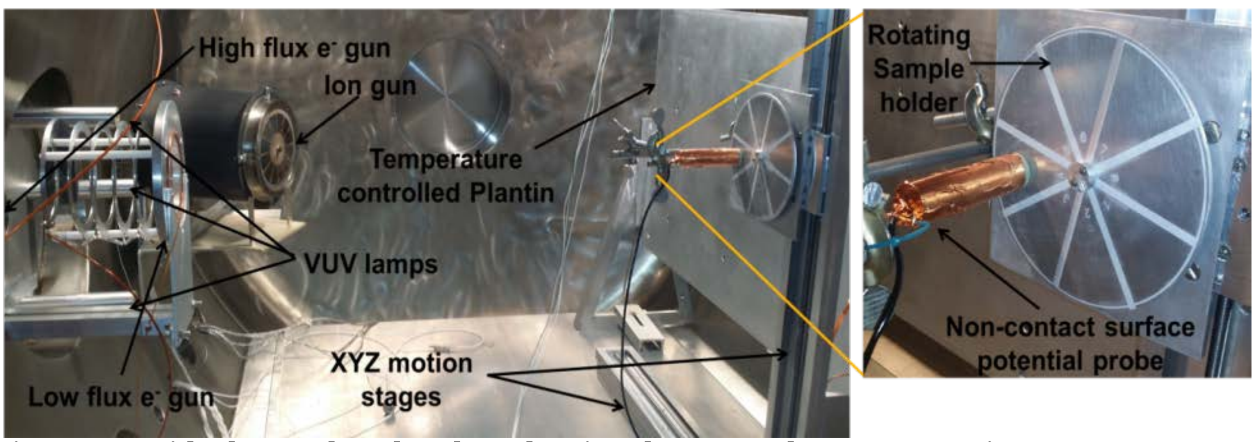

Figure 3: Inside the Jumbo Chamber Showing the Internal Instrumentation

4. PROBES

Jumbo contains several standard vacuum probes. There are ion and convectron gauges to measure the pressure in the chamber. We utilize the ion gauge as a vacuum interlock for both our electron gun and our non-contact surface probe. Jumbo also has an Extorr residual gas analyzer used to identify vacuum contamination and leaks in the chamber and a QCM is also available for precise cleanliness evaluation. Jumbo is also equipped with a variety of specialized probes that are used to quantify our various sources and to probe the surface voltage of the materials under investigation.

4.1 Source Probes

Jumbo has two Faraday cups. The first is a Kimball Physics, model FC-71A, used to monitor fluxes from the Kimball Physics electron gun. It has a 0.5 cm^2 aperture area and a retarding grid capable of 1000V in order to identify beam energy. We can both put voltage on the retarding grid and read the current output of the Faraday cup with a Keithley model 6487 source/meter. The Keithley meter has a detection limit 0.01 pA. However, our ammeter and Faraday cup system is

limited by the noise introduced from the Faraday cup cabling and the BNC feedthroughs on the chamber. The current detection resolution is 0.2pA/cm^2. This resolution is well below the normal fluxes we use in experiments and does not create much error in our measurement.

The second Faraday cup is actually a planar Faraday probe with a 0.5 cm^2 collection plate capable of being biased to ±500V manufactured by Plasma Contorols LLC. This probe allows for easy electron or charged species measurements. Positive bias results in rejection of positively charge ions and negative bias rejects negatively charged particles. This probe, in conjunction with a Langmuir probe, provides excellent plasma characterization.

Jumbo is equipped with a spherical Langmuir probe capable of measuring plasma potential, plasma density, and electron temperature of Jumbo's plasma source. It is a standard 3.175cm diameter Langmuir probe manufactured by Plasma Controls LLC. A Keithley 2410 high voltage source/meter is used to bias the probe and simultaneously record the current. This system uses the pulse sweep technique of measuring the electron temperature and density and is far less sensitive to surface contamination than traditional sweep methods.

4.2 Non-contact Surface Potential Probes

There are two different non-contact surface potential probes for Jumbo. Both probes are produced by Trek Inc. Trek probe model 370 is capable of -3 to 3kV and has an extremely fast, 50µs/kV response to changing surface potentials. Trek probe 341B is capable of -20 to 20kV with a 200 µs/kV response time. During our charging experiments the probe sits over a stationary sample for at least one second before taking the measurement, ensuring that both of our probes have more than sufficient time to measure accurately. These probes are critical to the experiments we are undertaking here as they can accurately measure the surface potential without bleeding any of the charge away. The difficulty in using a non-contact probe is that the material-to-probe distance is critical. The probes must be 3 mm ± 1 mm away from the samples. Mounting the sample carousel so that when rotated the sample/probe distance is constant can be challenging. The *in situ* cabling was placed in Teflon tubing to prevent arcing from the cabling and both the probe holder and tube were wrapped in Cu tape to prevent them from charging. Any charging on the insulators surrounding the probe or the cabling results in erroneous readings from the non-contact probe and consequently must be avoided.

5. ENERGETIC PARTICLE SOURCES

The energetic particle space environment is a complex and dynamic environment that can range in energy and flux over many orders of magnitude. For this reason it is impossible to simulate all aspects simultaneously and tradeoffs must be made to arrive at a practical system. We have focused on the electron and photon environment of GEO and the electron, photon and ion environment of LEO.

5.1 Vacuum Ultraviolet Lamps

In GEO the light most likely to damage polymer materials is the Lyman-α line of hydrogen at 121.6nm. This vacuum ultraviolet (VUV) light has enough energy (~10eV) to break bonds in polymer materials. This is also the region of the solar spectrum most responsible for generating

photoelectrons as these photons have energy greater than the band gap of most insulators. In order to mimic Lyman-α line of hydrogen, four Krypton lamps were acquired from Resonance Ltd. Krypton, with transitions at 123.6 nm and 116.5nm, fig. 4, is an excellent approximation for the Lyman-α line. Three of these lamps are mounted on 2 ¾ inch CF flanges in a circle around our high energy electron gun and perpendicular to the chamber axis and sample stage. These lamps are six inches from the center of the electron gun. A Hamamatsu phototube R1187 is used to measure the output of the VUV lamps using a Keithley model 6487 picoammeter. To map the uniformity of the spot, the photocathode was mounted on the three-axis translational stage and raster scanned over the range of the stages. The three lamps have nearly identical divergence of 40^o FWHM; however they produce different VUV fluxes.

The VUV flux is highly dependent on the cleanliness of the windows on the VUV lamps. Due to background contamination in the chamber, especially silicones, a thin residue forms on the windows when they are in use in the chamber. The Jumbo chamber is quite clean and all effort is made to minimize the contamination.

The solar flux of Lyman-α light is variable in GEO orbit but the average baseline for photon flux is 2.5×10^{11} photons/cm^2.[6] We calculate the equivalent suns of our lamps by dividing our photon flux by the literature GEO flux mentioned above. Equivalent suns at Lyman-α line produced by three Krypton lamps is plotted as a function of time in fig. 5. The lamps were cleaned well and then the chamber was pumped for three days before these data were collected.

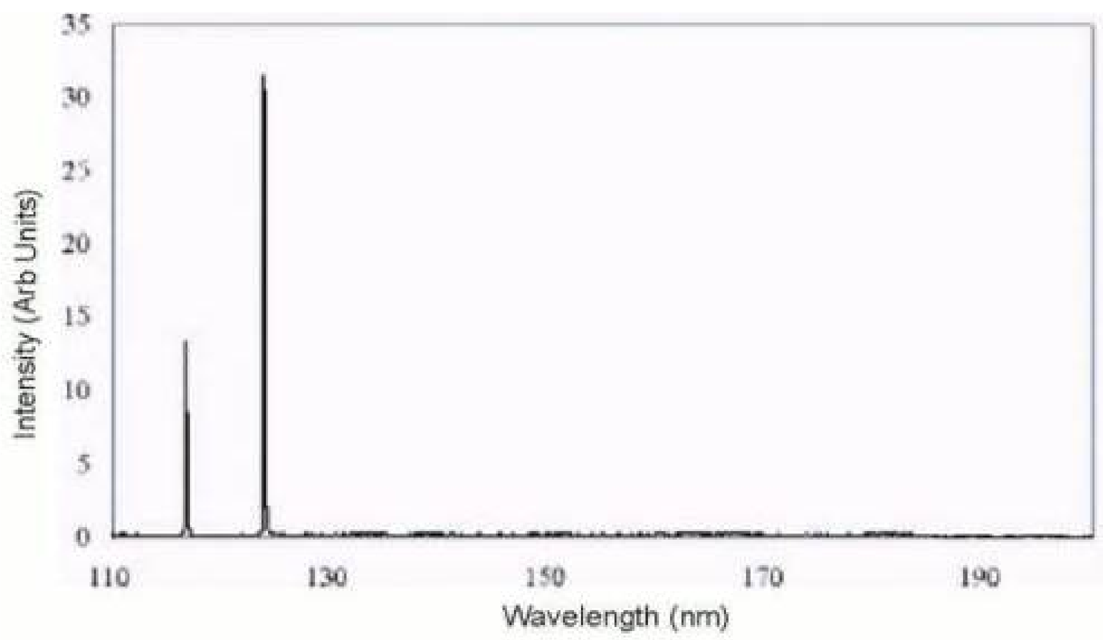

Figure 4: Spectrum of Kr VUV Lamps.

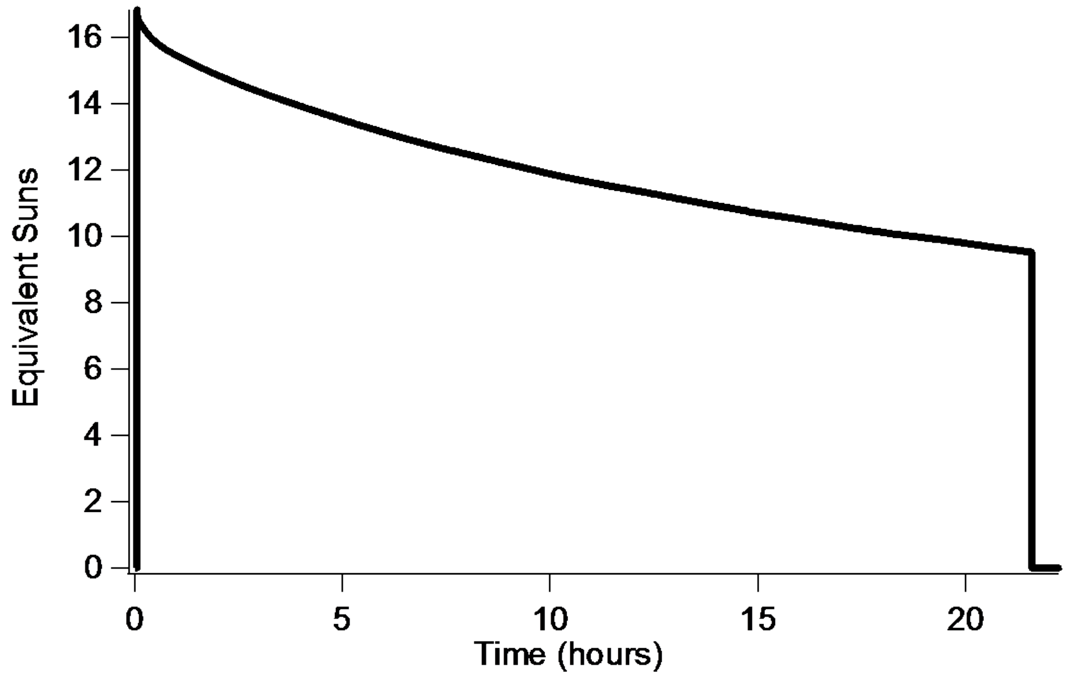

Figure 5: Lyman-α Intensity Falling Off as a Result of Contamination on the Lamp Window.

When using the VUV lamps, we clean them each time with aluminum oxide powder; however over the course of time (tens of hours) the total output of the lamp drops. Because the formation of this thin residue is proportional to the constant vacuum level it is easy to correct for this drop in VUV output by monitoring the VUV photocathode during lamp usage. We discussed this decrease with the manufacturer of the lamps and they noted that the decrease in output flux we see is smaller than they expect, indicating the cleanliness of our vacuum.

We are not able to control the divergence of the VUV lamps; however we can move the sample wheel in order to adjust the size of the beam and maximize the exposure of the samples to the VUV lamps in order to increase the VUV aging factor.

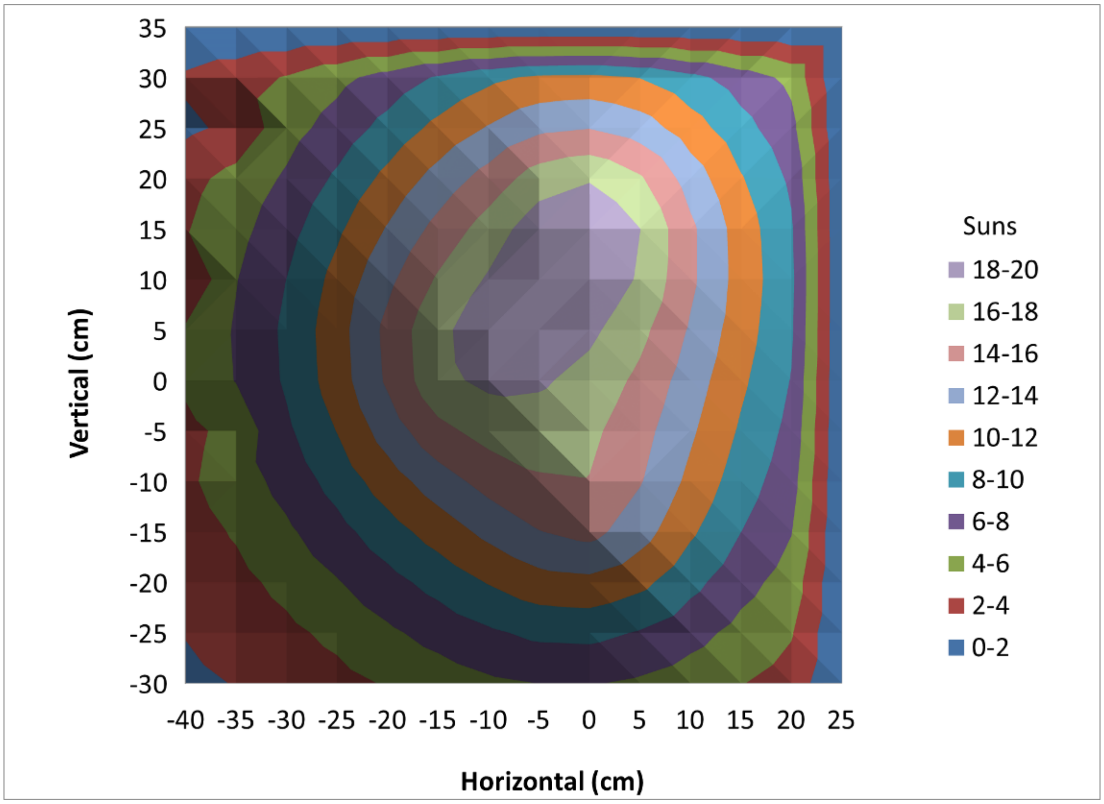

Figure 6: Map of VUV Intensity, Plotted as Equivalent Suns, of All Three Lamps at 22" From the Lamp Window

The map in Fig. 6 corresponds to the closest the sample holder can be placed to the VUV lamps with the 3 axis stages. The VUV lamps give a very uniform beam and the small amount of asymmetry in the VUV beam is due to the difference in flux from the different lamps. With these fluxes in mind and knowing the approximate VUV decrease due to contamination of the VUV window we can be confident that we will be able to expose our samples to > 10x GEO fluxes. This is the maximum from the VUV lamps, and we can control the RF field in order to decrease the VUV output in a controlled fashion.

5.2 Electron Gun

The prime electron source is a Kimball Physics EG8105-UD electron flood gun with a range of 1keV-100keV. This gun has two main purposes. First, a 20keV beam acts as a charging source by injecting shallow penetration (~5 µm) electrons into thin (25 µm) test materials. The flux of the electron gun is controllable from pA/cm^2 to tens of nA/cm^2. Low fluxes (50pA/cm^2) of 20keV electrons are used to simulate a flux that might be seen in GEO.[7] This flux is in the range of fluxes that materials would be exposed to in space in GEO. These fluxes also charge the samples at a rate that allows the materials to reach equilibrium in several hours, a time frame that allows us to capture the subtleties of the charging and to derive the underlying physics. The electron beam as it comes out of the gun at 20keV without focusing has a low divergence of <5º. This requires a rastering of the electron gun in order to create a larger electron beam and provide for a uniform exposure of the materials under investigation. Rastering is a systematic

perturbation of the electron beam angle by use of electromagnets to steer the beam in two dimensions. Appropriate raster settings to create a uniform beam of the appropriate size must be experimentally determined for each electron beam energy. It is important that the raster scan take place on a fast time scale relative to the sample rotation to ensure that there is no aliasing of the electron beam on the rotating sample holder leading to a non-uniform exposure. The maximum divergence of the raster scanned beam is 20º and the sweep rate has a range of 0Hz to 500Hz. We typically use smaller divergence rastering ~10º in order to uniformly expose our samples, Fig. 7.

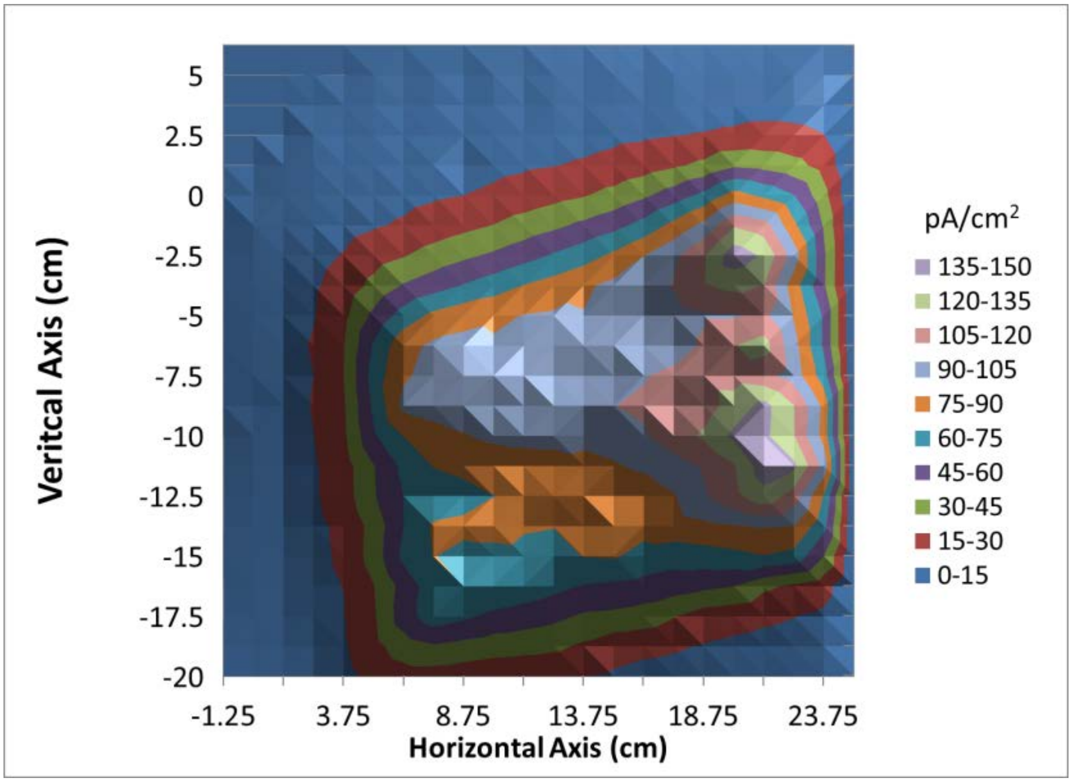

Figure 7: Beam Map of 20keV Electrons with Rastering.

The electron gun is also capable of running in pulsed mode. Although this capability is not currently in use, it provides the opportunity to look at materials exposed to highly controlled short bursts of electrons. This capability can be used to produce a continuous beam, single pulses of 2μs or a pulse train with a maximum frequency of 5kHz.

To measure the electron beam spot uniformity, maps are made using a Faraday cup mounted on the 2 axis translation stage. The position of the faraday cup is controlled with the stepper motors recording an average faraday cup reading at each point. There is an extensive automated program capable of moving the translational stages in discrete steps and recording the readings of various probes in Jumbo. This allows us to record the flux of various particles as a function of spatial location. This is critical to a precise knowledge of the environment we are exposing our samples to in Jumbo. The long term stability of the electron gun has also been determined by leaving the Faraday cup at a single point and recorded the current as a function of time. This indicates that

the rastering occurs on a time scale shorter than 0.5 seconds, much faster than the rotation of our wheel and consequently does not cause inaccuracy in our fluence calculations.

The beam shape is steady over long periods of time including multiple ventings of the electron gun. The electron flux does vary ~30%, especially after it is initially turned on, but this is overcome by allowing the gun to warm up for several hours before making any measurements, typical flux stability is shown in Fig 8. Additionally, during material exposure to the electron beam the flux is recorded using the Faraday cup. This gives a very accurate measurement of the absolute flux which is critical for calculating the amount of aging and is also used in the fitting of charge/discharge curves of materials under investigation.

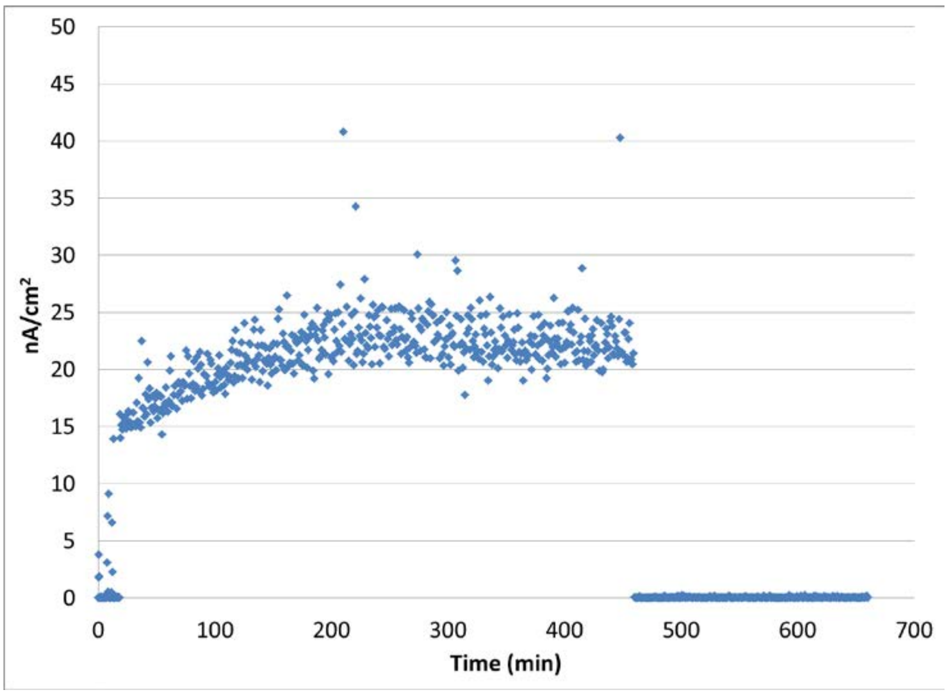

Figure 8: Electron Beam Flux at 90keV With Rastering as a Function of Time.

In addition to using the electron gun to test the charge transport characteristics of materials it is also used to age materials. A high energy on the electron gun, 90keV, is used to fully penetrate the thin materials we are studying here. We calculate the dose the material receives by assuming the continuous slow-down approximation of energy deposition within solids. The gun flux is capable of tuning to simulate 12 months of dose in an average GEO environment in 8 hours over our entire sample wheel, Fig. 9. This allows for testing of highly aged materials in short periods of time.

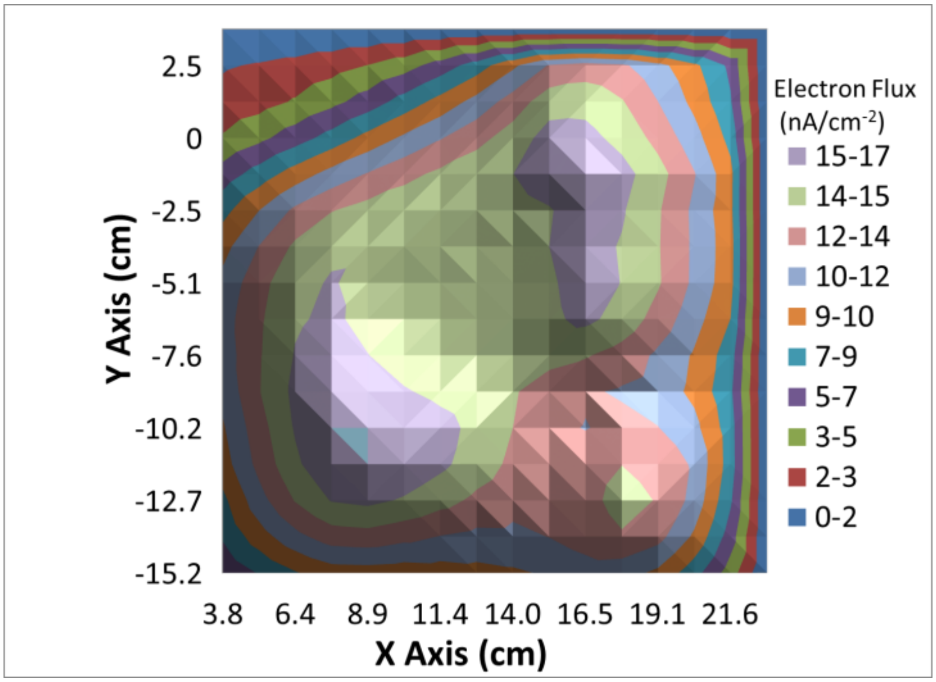

Figure 9: Beam Map of 90keV Electrons with Rastering.

All aspects of Jumbo are controlled with LabVIEW, Fig. 10. The program controls the rotation of the sample carousel, controls the various sources in our chamber, and monitors the outputs from the various probes. This automation gives the capability to record the surface potential of various materials using the surface potential probe while rotating the sample holder and controlling the flux of electrons that the materials , to determine the extent to which they charge. The control software is robust and allows for continuous testing for weeks without human supervision.

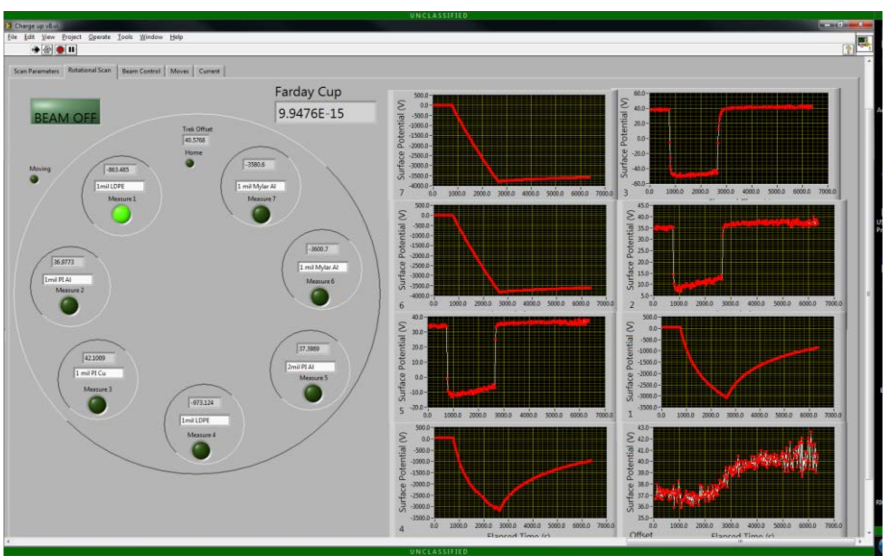

Figure 10: Front Panel of LabVIEW Automated Control Program.

The rotating sample wheel exposes all samples on the wheel to the same environment. To test this, we placed three samples of 2 mil polyimide (PI) backed with Al on the sample wheel at different positions and exposed them to 20keV electrons and measured their surface potential as a function time. A deep understanding of the physics in play is not necessary to see that all of the samples behave in the same manner, Fig. 11. This shows that sample location does not play a role to the environment that the samples are exposed to.

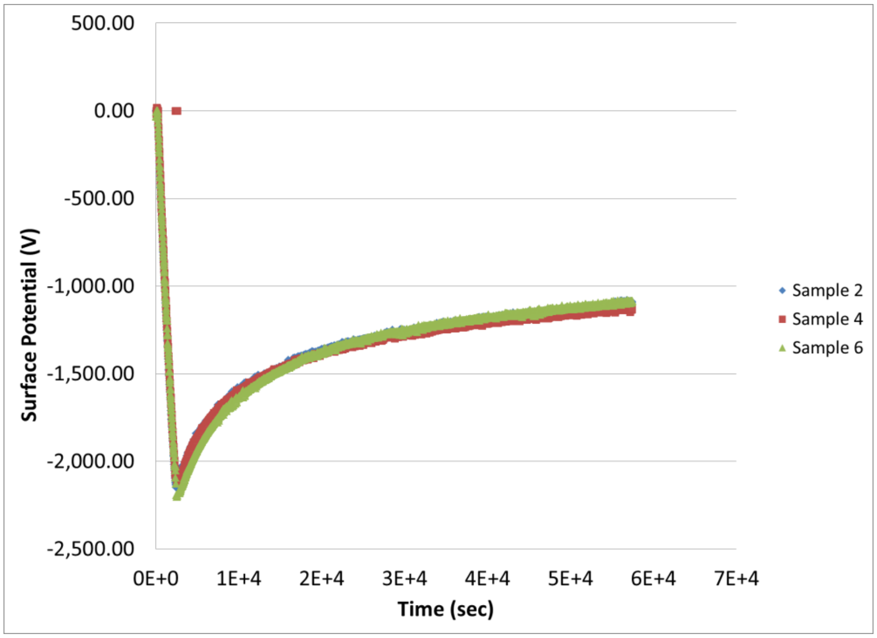

Figure 1: Charge and Discharge Curves for Three Identical Samples of PI Mounted at Different Positions on the Sample Wheel.

6. CONCLUSIONS

The Jumbo environmental chamber has been up-dated to provide a state-of-art facility for the testing of space-based systems. Its sources and probes have been extensively tested and characterized, allowing the introduction of many experimental apparatuses in addition to the charging work currently underway. The high degree of automation gives the system great flexibility and it can largely be operated in a “hands off” manner. The various sources have been shown to be stable with a high degree of repeatability, even after repeated chamber venting. These sources and capability to control the temperature down to 97 K provide a versatile tool for the study of environmental interactions.

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